GEM: a Participatory Framework for Open, State-of-the-Art Models and Tools for Earthquake Risk Assessment

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SUMMARY
The Global Earthquake Model (GEM) initiative aims to develop a global model of earthquake risk as an open source, community-driven project. In order to begin this in a structured way, a number of global components that cover the scientific modules of the model were defined and international consortia were invited to bid and lead these their development. These consortia define standards and best practice related to the methodologies used in seismic hazard and risk assessment and in particular the collection and storage of data needed therein. This paper introduces these global components and describes an open source platform for risk assessment OpenQuake that is being developed to provide access to and interaction with the proposed data and tools.

Keywords: global, seismic hazard, seismic risk, community, open source

1. INTRODUCTION TO THE GEM INITIATIVE

Almost half a million people died in the last decade due to earthquakes. Most of these casualties were in the developing world, where risk continues to increase due to rapid population growth, urbanisation and poor construction practice. The recent earthquakes in Haiti, Chile, Japan and New Zealand painfully reminded the world of the destructive impact of seismic events and the importance of reliable earthquake risk information. Yet, in many earthquake-prone regions risk models or advanced tools for risk assessment do not exist or are inaccessible due to their proprietary nature. State-of-the-art information on earthquake risk covering all areas of the world however constitutes a critical puzzle-piece for minimising loss of life, property damage, and social and economic disruption due to earthquakes, through improved buildings codes and construction, sustainable land use planning, improved emergency response, protection of critical infrastructures and greater access to insurance. There is hence a need for such information to become accessible to a wide spectrum of stakeholders (such as engineers, researchers, risk managers, urban planners, insurers/reinsurers, civil protection departments, international and non-governmental organisations) and their beneficiaries. This need was underlined by a call from the Organisation for Economic Cooperation and Development's (OECD) Global Science Forum for development of open-source risk assessment tools, and has been confirmed by a variety of institutions and organisations, the scientific community, and public opinion. In response to the needs outlined above, GEM was set up to collaboratively build state-of-the-art, widely accepted datasets, models and software/tools for the assessment of seismic risk on a global scale and to develop a supporting IT infrastructure.

1.1 Global Earthquake Risk Modelling

Users across the globe will be able to access the basic datasets, models and accompanying tools through GEM's risk assessment platform (called OpenQuake), of which a first version will become available early 2014. The platform will allow users not only to perform hazard and risk analyses, but also to make decisions on retrofitting and insurance and collaborate and exchange data, results and opinions amongst each other. It is envisaged that the datasets and models will be continuously evolving due to community input and collaboration, and hence OpenQuake is being built in such a way that it can capture the world's best understanding of data, the earth and earthquake behaviour, and the built environment at any given moment in the future. The ultimate aim of GEM is to create a global earthquake risk model that is as homogenous as possible, based on hazard and risk models that explicitly account for epistemic uncertainties though logic-trees, and that relies on highly reproducible procedures. Within GEM's first working programme (2009-2013) it will not be possible to incorporate all the data effectively available, nor cover all the countries in the world in a uniform way. Also, it is unlikely that secondary hazards such as tsunamis and landslides will be covered within the first set of models. During its first working programme GEM will hence create tools and standardised methods for obtaining and analysing data, which allow collaborators and affiliated researchers around the globe to begin the process of assembling the needed (global) datasets, hereby producing data coverage for the world that is more uniform and complete than before.

1.2 Scientific Modules

GEM's global earthquake risk model is based on a probabilistic framework and consists of seismic hazard (represented by the exceedance probability of levels of ground shaking resulting from earthquakes, within a given time span), vulnerability (defined as the probability of loss given a level of ground shaking for physical vulnerability, or through indicators that envelop the socio-economic factors known to be driving forces of vulnerability), and exposure (the elements at risk). Combining these components within the risk module allows for an estimation of direct damage and loss as well as risk indices. Indirect economic loss and the long-term impacts of earthquakes fit within the risk and impact analysis module and then decision-making tools can be built on top of the aforementioned output. The development focus within GEM is on the components of hazard, physical vulnerability and exposure, calculation of direct losses (total losses and insured losses), complemented by derivation of indices for social vulnerability and disaster resilience for calculation of total risk, and decision support tools that consider the cost-benefit analysis of retrofitting and insurance.

Fig 1. Scientific Modules of GEM

1.3 Collaborative Development

GEM believes that global risk assessment can only be carried out in cooperation with the community and be readily adopted because the community believes in it. Experts and professionals worldwide working on issues related to seismic hazard assessment, risk assessment and risk management form the core of GEM's "community". Hundreds of renowned institutions and professionals in the relevant disciplines are developing the datasets, models and tools that will form the core of GEM's model.

The GEM initiative advances by means of 'building blocks'. The first one was the GEM1 pilot project, which ended in March 2010 and delivered a proof-of-concept in terms of preliminary global hazard and risk calculations and an initial model-building infrastructure. Currently, development is based upon the core efforts of the Global Components, Regional Programmes and the Model Facility (see figure 2). GEM's Executive Committee brings the activities of these three core elements together; a process which is monitored by GEM's Scientific Board. Dedicated groups of leading experts from GEM's Technical Advisory Pool are formed to further support the process.

- *Global Components* (GC) projects [1] are carried out by international consortia that are selected after a thorough process of expert elicitation, community feedback, and peer review. Experts and stakeholders can provide feedback on the work through GEM Nexus.
- *Regional Programmes* provide feedback on development of the Global Components, work on data collection and create regional input models for GEM.
- The *Model Facility* (MF) oversees development of the OpenQuake risk assessment platform and of the OpenQuake engine that will power hazard and risk calculations at any scale. The software is developed in an open environment, which allows a wider community of developers and expert-users to jointly enhance it. A dedicated Testing and Evaluation facility will test datasets and model components before they are released to the public.

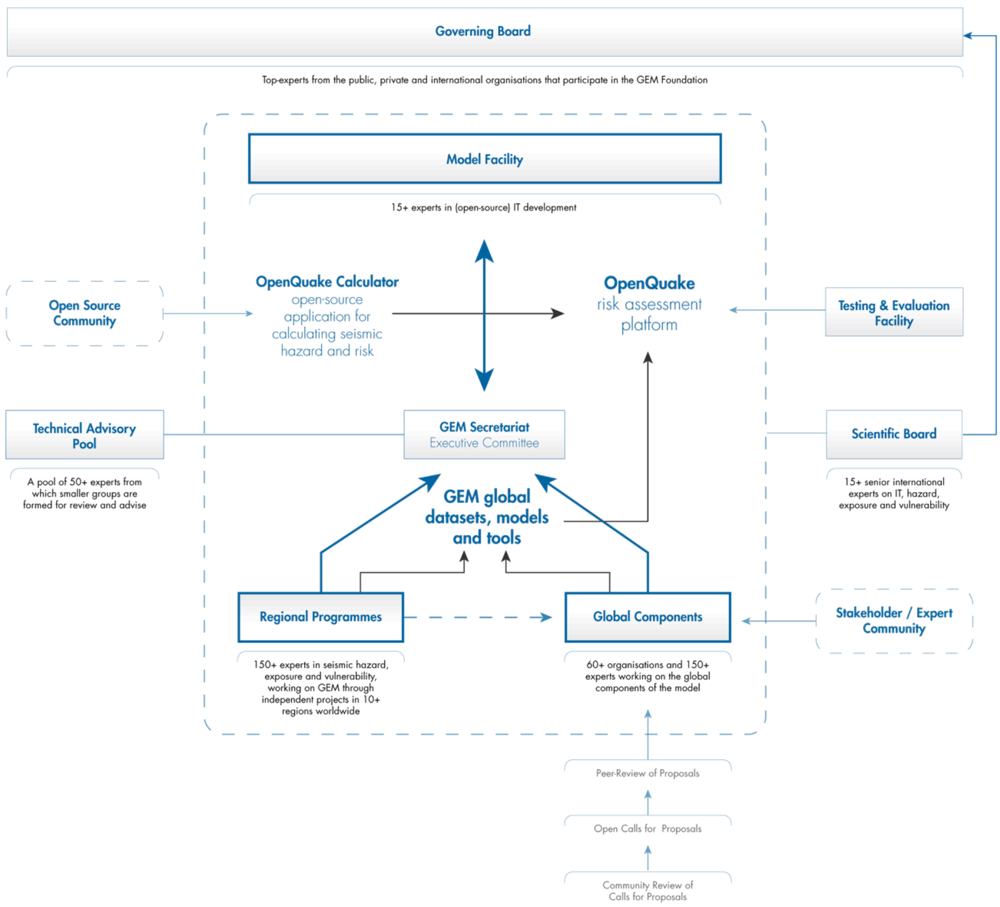

Fig 2. GEM's development infrastructure

To support collaborative development, a website has been developed for GEM collaborators, experts and practitioners in seismic risk assessment to collaborate, share and discuss. GEM Nexus [2] provides the various groups working on GEM with a set of collaboration instruments and is open to the wider (scientific) community to follow the groups and provide feedback on their work. From 2014 onwards, the OpenQuake platform will allow researchers, agencies, and institutions to adopt and enhance the tools, provide comments and populate the datasets, so as to continuously enhance global risk assessment. Such process of 'crowdsourcing' is obviously closely monitored and data quality-controlled to ensure highest quality of data and compatibility. It is hoped and envisaged that scientists, practitioners, IT-experts and others will make use of the critical research gaps that we highlight, to collaborate with us and collectively work on making the datasets, models, and tools of better use for all stakeholders worldwide, in that way contributing to the continuous improvement of the risk assessment at a global scale.

2. GLOBAL COMPONENTS DEVELOPMENT

GEM is funding five hazard Global Components projects planned to prepare global datasets with basic information necessary to create probabilistic seismic hazard analysis (PSHA) input models. All five projects started in 2010. Requests for Proposals for 5 Global Components related to Physical Risk were drafted by a focus group and subsequently modified based on the feedback from the community through the online commenting system on the GEM website. It is noted that during this first 5-year phase of GEM, the emphasis is placed on the seismic risk of buildings (residential and commercial) due to budget and time constraints, whilst future extensions are expected to consider infrastructure/lifelines. Following a discussion and iteration process of more than a year related to measurement and incorporation of socio-economic impact of earthquake events, a project on social vulnerability and disaster resilience was initiated at the start of 2012. The project directly supports GEM's mission of producing a holistic global earthquake risk model.

2.1 Global Earthquake History

The Global Earthquake History is compiling an archive of historical earthquakes studies and a global parametric catalogue called Global Large Historical Earthquake Catalogue (GLHECAT) containing events with magnitude $M \geq 7.0$ that occurred in the temporal window 1000 and 1903AD. The catalogue is compiled by critically merging catalogues (e.g. Utsu, 2002 or Dunbar, 2009) or datasets taken from published and publically available material. The catalogue and the archive build upon AHEAD (see http://www.emidius.eu/AHEAD/main/). This project aims to produce the first global collection of historical events that - for each event in the catalogue - provides a comprehensive compilation of the most recent studies, as well as the original studies referenced by the catalogue's authors, to infer the main parameters describing the event. The catalogue is largely dynamic, which allows for future updates and improvements. Moreover, this catalogue and the related archive represent an important step in the creation of a global homogenized earthquake history and already proves to be an extremely important information source for PSHA. This two-year project is coordinated by two leading institutions: INGV (Italy) and BGS (UK).

2.2 Global Instrumental Catalogue

The International Seismological Centre (ISC) in collaboration with a team of international experts and feedback from a number of IASPEI observers, is leading this initiative aimed at the creation of a homogeneous instrumental seismicity catalogue for the period 1900-2009. This global catalogue of earthquakes will contain about 25.000 events. In the interval 1900-1917 the catalogue will comprise events with magnitude greater or equal to 7.5; from 1918 until 1959 it will have events with magnitude greater of equal to 6.25 and, finally, from 1960 on the catalogue will include earthquakes with magnitude equal or greater than 5.5. The catalogue will be composed of earthquakes with homogeneous locations and magnitude estimates, determined using the same tools and techniques to the extent possible. The magnitude determination and location procedures applied represent a synthesis of state-of-the art methods. Each event will have a M_W value (with related uncertainty) based on seismic moment where possible (mainly for the events occurred in the window 1976-2009); in the other cases, empirical relations between M_W and M_S/m_b will be used to obtain proxy values of moment magnitude. Most of the events in the pre-1971 period will have their M_S magnitudes computed in a systematic manner from the surface wave amplitude measurements recovered from the historical paper-based seismic station bulletins. These M_S magnitude were never available before; they are the results of a massive data entry effort completed under this project.

2.3 Global Active Fault and Seismic Source Catalogue

The GEM Faulted Earth project, coordinated by GNS Science (New Zealand) and Earth Observatory Singapore is creating a database of active faults and faults sources following a common set of strategies, standards and formats. The consortium has already created an archive of existing national or international databases to better comprehend the state-of-the-art and produced a database schema able to gather the information currently available in different formats. The final database will contain information relative to active shallow faults and folds and subduction sources (using for example the SLAB 1.0 database - http://earthquake.usgs.gov/research/data/slab/). Further on, the database will be considerably extended with contributions from various regional groups; the compilation of the database with new information will be assisted by an interface that is currently being created by the GEM Model Facility as a component of the OpenQuake platform (see Fig 3). Data collected in this project will constitute a fundamental input to the suite of tools that GEM is creating to assist hazard modellers in creation of PSHA state-of-practice input models.

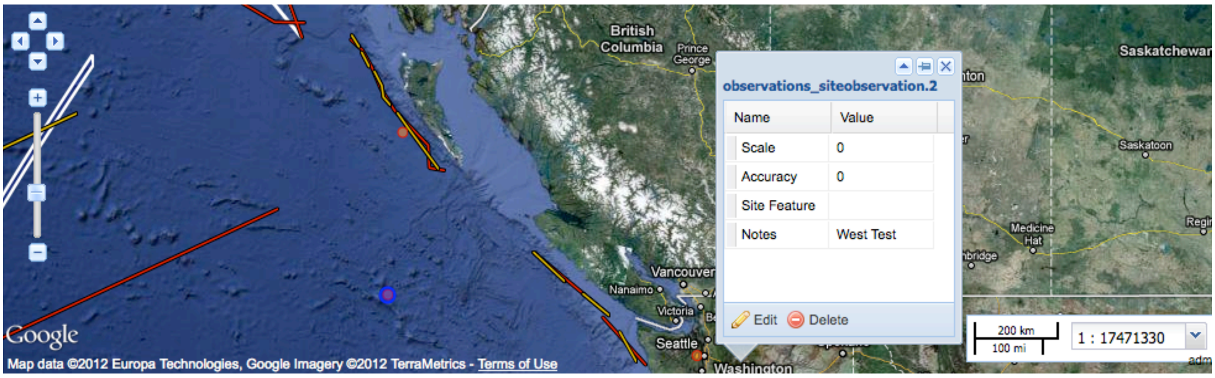

Fig 3. Faulted Earth tool for capturing data on faults collected by geologists. Note that the lineaments represented are just for demonstrative purposes.

2.4 Global Geodetic Strain Rate Model

Strain rate is an important and independent source of information that can be used as a proxy for earthquake potential. The GEM Global Geodetic Strain Rate Model project is taking advantage of the experience gained in the global strain rate map project (Kreemer *et al.*, 2003) to develop a numerical model of strain rate obtained from 10,000+ GPS measurements of plate motion, covering the most important deforming areas of the globe. The model will be based on secular horizontal velocities obtained from a dataset of some 4000 continuous GPS stations unevenly distributed on the globe, with the addition of thousands of published campaign-style observations. The resolution of the models will be 0.2° instead of 0.5° as in the current model. This new model will be the most updated version of the homogeneous global strain rate model that was developed in 2004. Principal Investigators from the University of Nevada (USA), Ecole Normale Supérieure (France), University of California/CEA (USA) and UNAVCO are overseeing the tasks.

2.5 Global Ground Motion Prediction Equations

The main goal of this project is the development of a harmonized and tested suite of ground motion prediction equations (GMPEs) that can be used at both the global and regional level for hazard and risk assessment, built on the most recent advancements in the field. The consortium is defining a consistent strategy for modelling ground motion by analysing the consistency in model parameters and site parameters. A second important task is selection and critical review of a large set of GMPEs. By using information that is made available through comprehensive collection of waveforms, this set is then used for definition of a global set of recommended GMPEs. The consortium will also work on the inclusion of near-fault effects and on specifications for compilation of a global database of soil classification. The Pacific Earthquake Engineering Research Center (PEER) leads the project that furthermore features active participation of 27 international experts.

2.6 Ontology and Taxonomy

Ontology refers to the entire framework that will guide GEM's development – the set of concepts, and the relationship between those concepts that will allow determination and communication of earthquake risk, and Taxonomy is a part of the ontology, and refers to the classification of things in an ordered system. GEM's Ontology is being developed iteratively through the work of the Global Components projects and the development of the OpenQuake tools. On the other hand, a group of experts being led by the Alliance for Global Open Risk Analysis (AGORA) has been tasked within this global component to develop a building taxonomy, classifying the attributes of building typologies around the world. Version 1.0 of the Basic Building Taxonomy is available from GEM Nexus [3]. Taxonomies for other components within hazard and risk assessment such as seismic sources and soil conditions are envisioned for future development. The terminology used in Ontology and Building Taxonomy is being collected into a GEM Glossary that will be made available for review and comments from the wider scientific community on GEM Nexus.

2.7 Global Exposure Database

This project aims to create the first open database of global building stock and population distribution containing the spatial, structural, and occupancy-related information necessary for damage, loss and human casualty (estimation) models to be deployed in GEM. The project goes by the name of GED4GEM and is aimed at managing three main tasks:

- Collection, analysis and homogenisation of global databases that may be available and useful for the global exposure database;
- Definition and implementation of a global exposure database based on the output of task 1;
- Definition of "best practices" aimed at populating missing layers and/or information in specific geographical areas.

The consortium started by building on existing databases (e.g. UN, regional and other public organisations, governmental building census data, and national statistics) and published literature. It currently aims to collect population and building stock data for all countries of the world. The global exposure database (GED) is being built by combining raw datasets with inference algorithms which will have two levels of detail; the first level is a global set of points representing 30 arc-second quadrilaterals (which can be converted to raster layers with approximately 1km resolution), with associated aggregate building and population information, the second level of detail accommodates individual buildings as vector data. Each grid cell will include aggregate information on the population and the number/built area/reconstruction cost of residential buildings, standardised to a common timestamp (2012). The distribution of building typologies, classified with a number of attributes including material, lateral load resisting system, height (as described in the GEM building taxonomy) and the occupancy of different building typologies during the day and night will be stored. Building-by-building data will also be available for a select number of areas; this data is expected to increase with time through the use of the Inventory Data Capture Tools. The partners making up the consortium are: the University of Pavia (coordinator), CIESIN-Colombia University, IES-CEA, IGP-CEA, ImageCat, JRC, and UN-HABITAT. The USGS and EUCENTRE are advising partners.

2.8 Global Physical Vulnerability Estimation Methods

The physical vulnerability project has 3 year-duration and involves 9 partners worldwide: University of Colorado at Boulder, University of Chile, Geoscience Australia, EERI, Stanford University, University College London, University of Bath, USGS and Willis. The project focuses on relationships between earthquake shaking intensity and physical building damage or related loss, relationships often called seismic (physical) vulnerability functions (Fig 4). The project has two central objectives: to develop procedures for deriving physical vulnerability functions, and to actually implement those procedures and produce vulnerability functions for a wide variety of building types, following the GEM building taxonomy. The project will not produce seismic vulnerability functions for every building type everywhere in the world, but it will most likely provide a major advance, both in terms of a library of physical vulnerability functions and standardised procedures for adding to that library. The project will address four distinct approaches to creating seismic vulnerability functions: empirical (using regression analysis to derive seismic vulnerability functions from past observations of earthquake loss experienced by real buildings of a particular type), analytical (using first principles of structural engineering to relate damage and loss to shaking intensity), expert opinion (elicitation of the judgment of experts familiar with the building type of interest to produce a seismic vulnerability function), and empirical-national (seismic vulnerability functions are developed for entire countries, or large sub- and supranational regions, without regard to building type, to best fit past loss data).

The consortium furthermore endeavours to develop procedures for aiding selection among competing seismic vulnerability functions based on a quality rating with 5 indices: data quality, relevance, rationality, documentation and on overall quality; to relate building damage to human casualties and repair costs; to deal rigorously with uncertainties in the capacity, response, collected data etc.; to apply different regression techniques in the derivation of vulnerability functions and identify the optimum intensity measures for different building typologies; to update seismic vulnerability functions as new data become available through Bayesian Updating; to use empirical data for testing analytical functions; and to ensure that the outputs serve the needs of loss-estimation practitioners.

2.9 Global Earthquake Consequences Database

An international consortium is developing a database of the consequences (in terms of damage, casualties, socio-economic consequence and recovery data) of past earthquakes due to ground shaking, landslides, liquefaction, tsunamis and fire for a number of different structures and infrastructures. This database will serve to inform users on consequences from past events, as a benchmarking tool for analytical loss models and to support the development of tools to create vulnerability data appropriate to specific countries, structures, or building classes. Preparation of an interface enabling the impact damage from future earthquakes to be captured and uploaded to the database is also part of the project, to ensure that consequence data that is of relevance today is available for the derivation of empirical vulnerability functions, and for using the data for testing analytical functions. The data will be stored following the GEM building taxonomy, such that empirical vulnerability functions (following the guidelines of the physical vulnerability consortium) can be produced, using if desired the outputs of ShakeMap (USGS) for the description of the ground shaking from these events. This project, which is called 'GEMECD' has a 3 year duration and involves 10 partners worldwide: CAR Ltd, CRED, ERN-AL, GNS, KOERI, Kyoto University, Munich Re, SPA Risk, and USGS. The web accessible database will be integrated into the OpenQuake platform. For current events, the database will serve as a clearing-house of information, posted by users based on the standards and protocols set in the GEMECD documentation. In the long term, the database will be a repository of the most relevant and validated data on consequences of the significant events of the last 40 years around the world.

2.10 Inventory Data Capture Tools

The Inventory Data Capture Tools (IDCT) project (Bevington, et.al., 2012) addresses the inventory and damage data development needs of future users, in developing input to the Global Exposure and Global Earthquake Consequences databases. The project aims to provide a fully operational, flexible and integrated suite of tools, protocols and guidelines that are scientifically founded, yet straightforward to use. The project capitalises on the state-of-the-art in remote sensing, GIS, field tools for building data collection, inference and extrapolation methodologies and data integration techniques. A number of tools will be made available from handheld devices for recording the attributes of individual buildings, to remote sensing tools for the identification of homogenous areas or for delineating building footprints. A tool for crowdsourcing inventory and damage data collection through the OpenQuake platform will also be developed. The project has a duration of 30 months and involves the following partners: ImageCat, University of Pavia, CAR Ltd, CEDIM-GFZ, SPA Risk, BGS, WAPMERR, whereas Google and Willis are advising collaborators.

2.11 Social Vulnerability and Disaster Resilience

When extreme events intersect with societies they become disasters, and the impacts from disasters are rarely suffered equally across space and time. For the social vulnerability and disaster resilience initiative of GEM, the starting point is to address the differential susceptibility of populations to the adverse impacts of earthquake events. The project focuses on implementation of methods, metrics, and tools for the holistic evaluation of seismic risk. Composite indexing will be used to allow for the comparison of overall risk as defined by the seismic hazard, exposure, and the physical and socio-economic vulnerability and resilience of populations. The project will produce indices and tools for use at various geographic scales, that will be integrated into the OpenQuake platform:

- A social vulnerability index and database to define the susceptibility of populations to adverse impacts and loss,
- A disaster resilience index and database to gauge the ability of populations to respond to and recover from damaging events,
- An indirect loss index and database as a measure of indirect economic loss vulnerability
- A toolbox for development of composite indices, by using the indicator data mentioned above
- Tools for integrated risk assessment, supporting comparison of overall earthquake risk

Integrated risk assessment tools will support users in determining the relative contribution of different factors to overall risk and hereby increase awareness and understanding. Furthermore by reevaluating selected benchmarks periodically, the tools support monitoring of trends in earthquake risk over time, which contributes to measurement of the effectiveness of risk reduction strategies.

3. OPENQUAKE

As mentioned previously, GEM has set up a Model Facility whose mandate is to undertake the development of the OpenQuake platform that will integrate hazard and risk assessment tools and data and provide these to a wide range of stakeholders, including the scientific community.

The software that will power regional and global hazard and risk calculations within the platform (also called OpenQuake) [4] was openly released in January 2011 through an open source development platform and is now also provided as a web-service to allow interested scientists and other stakeholders to try the software. For what concerns hazard calculations, the OpenQuake engine will allow users to obtain the following outputs through classical PSHA or through a stochastic event-based approach (see also Monelli, *et.al.* 2012):

- Hazard curves and hazards maps (for different probabilities of exceedance within a given time span); the mean, a given fractile, or for each branch of the logic tree;
- Stochastic event sets and associated ground-motion fields;
- Disaggregation plots in terms of different combinations of magnitude, distance, epsilon, tectonic region type
- Uniform Hazard Spectra.

For physical risk calculations, the OpenQuake engine will allow users to obtain the following results, through a number of different methodologies (see also Silva *et. al.*, 2012):

- Loss exceedance curves (loss versus probability of exceedance in a given time span, both for single assets and portfolios of assets);
- Conditional loss maps describing the geographical distribution of values of loss with a fixed probability of exceedance in a given time span;
- Mean loss maps describing the geographic distribution of mean loss within a given time span;

- Damage maps describing the geographical distribution of mean number/area/percentage of damage at a given limit state for a given deterministic event;
- Loss statistics per event or across all events (mean loss, standard deviation of loss, etc.)

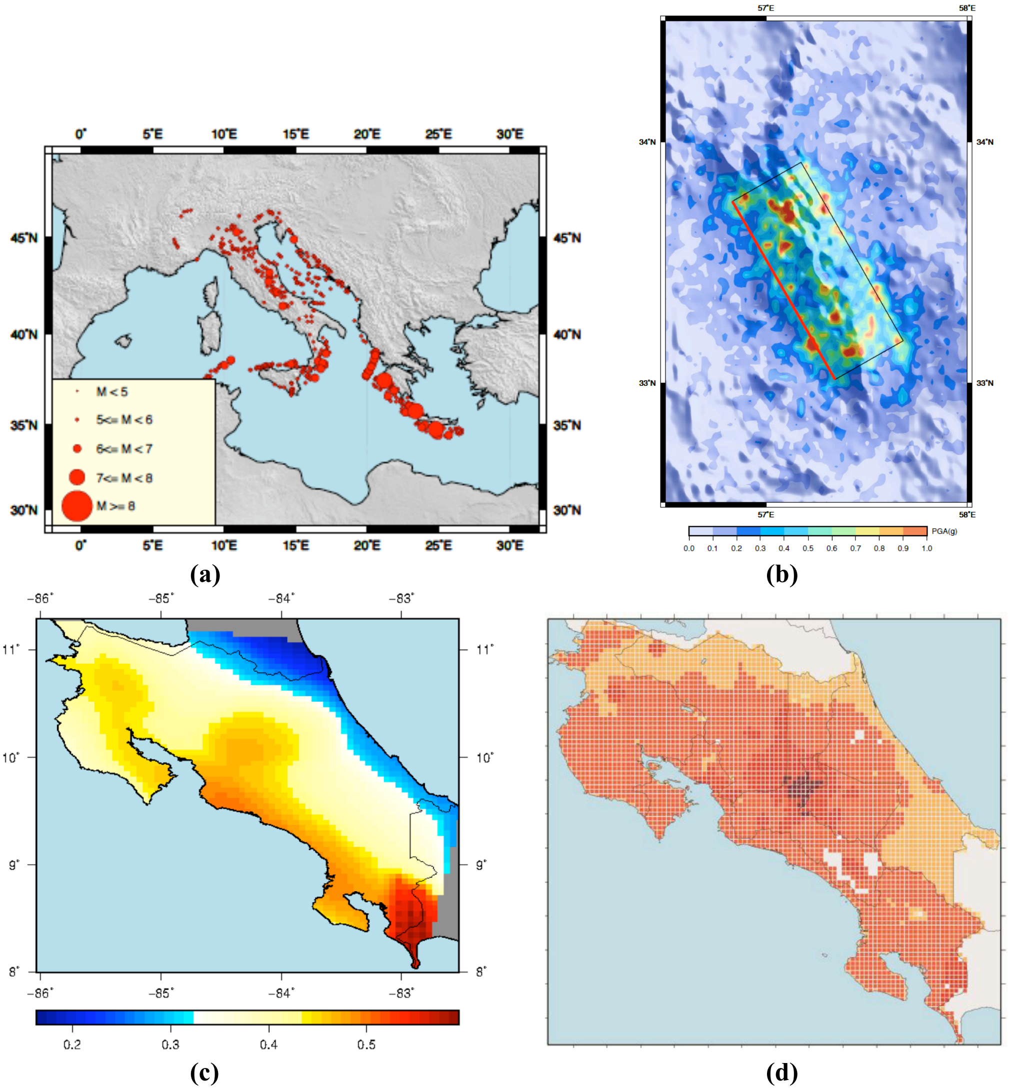

Fig 5. Various typical outputs of the OpenQuake engine (a) a stochastic event set, (b) a ground-motion field with spatial correlation of ground-motion residuals, (c) a seismic hazard map with 10% probability of exceedance in 50 years, (d) a loss map in terms of fatalities with 10% probability of exceedance in 50 years

Users will be able to interact with the global datasets and models through the OpenQuake risk assessment platform. Commercial use of the platform will have a cost, in order to support academic use and basic use worldwide. Reports and manuals with background to the science and tools will also be available, and spaces where users can share, discuss and help improve them. There will be several suites of the OpenQuake platform, attuned to the needs of the various groups GEM aims to serve. The most advanced suite is meant for academia and for any organisation or governmental agency that would like to do custom hazard and risk assessment and carry out its own modeling and calculation. It is a comprehensive suite of tools for exploring unique global datasets, PSHA, exposure and vulnerability models, indices for social vulnerability, pre-calculated hazard and loss maps for the entire globe, and other pre-calculated output. Users will be able to select GEM models as input to calculations, or import their models of choice (parsers will ensure compatibility of the models of other initiatives with GEM's Natural hazards Risk Markup Language, NRML) and make them suitable to be run on the platform. The suite will furthermore contain an extensive toolkit for modeling and pre-processing data as input for seismic hazard, loss and risk calculations with own or combined datasets.

Experts can capture new data, which after quality control will find its way into the applicable databases. And there are tools for post-processing data, performing cost-benefit analyses, and other tools that support decision-making. Other suites of the OpenQuake platform will be attuned to the needs of those users that prefer to not calculate hazard or risk themselves, but rather use GEM-developed maps, curves and other risk information. They will be able to explore seismic hazard and risk by zooming in to their area of interest, to overlay maps and use decision-making support tools.

4. OUTLOOK FOR GEM

GEM strives to be a community-driven initiative, and provides a number of mechanisms for those interested in seismic risk to become a part of the development process. This chapter has focused on the global components projects (that were initiated in 2010), which involve a large number of international organisations and expert individuals. These projects have kick-started the scientific activities, but GEM will rely on a large network of parties to develop its model, e.g. the members of the Governing Board (which includes both public and private participants), the Scientific Board (with experts in hazard, risk, socio-economic issues and IT), the Technical Advisory Pool (see Fig 2), those involved in Regional Programmes, the users of GEM Nexus, those providing comments on the website, software developers from the open source community, as well as governments, organisations and even individuals providing data to the OpenQuake platform.

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